USAARL REPORT NO. 83-8

TEMPORARY THRESHOLD SHIFTS PRODUCED BY EXPOSURE TO LOW-FREQUENCY NOISES (Reprint)

By

John H. Mills and J. David Osguthorpe
Department of Otolaryngology,
Medical University of South Carolina

C.K. Burdick
U.S. Army Medical Research and Development Command
Fort Detrick, Frederick, Maryland

J.H. Patterson and Ben Mozo
U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

May 1983

USAARL

NOTICE

Qualified Requesters

Qualified requesters may obtain copies from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia. Orders will be expedited if placed through the librarian or other person designated to request documents from the Defense Technical Information Center.

Change of Address

Organizations receiving reports from the US Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

Human Use

Human subjects participated in these studies after giving free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Reg 70-25 on Use of Volunteers in Research.

Reviewed:

Bruce C. Leibrecht
BRUCE C. LEIBRECHT, Ph.D.
MAJ, MSC
Director, Sensory Research Division

Kent A. Kimball
KENT A. KIMBALL, Ph.D.
Director, Extramural Research Program

Roger W. Wiley
ROGER W. WILEY, O.D., Ph.D.
LTC, MSC
Chairman, Scientific Review Committee

Released for Publication:

Dudley R. Price MC
DUDLEY R. PRICE
Colonel, MC, SFS
Commanding

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER USAARL Report 83-8	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Temporary Threshold Shifts Produced by Exposure to Low-Frequency Noises (Reprint)		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John H. Mills, J. David Osguthorpe, C. K. Burdick, J. H. Patterson and B. Mozo		8. CONTRACT OR GRANT NUMBER(s) DAMD 17-79-C-9180
9. PERFORMING ORGANIZATION NAME AND ADDRESS SGRD-UAS-AS US Army Aeromedical Research Laboratory Fort Rucker, Alabama 36362		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102A 3E161102 BS07 00T1SG 61102A 3M161102BS10 CB282
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Aeromedical Research Laboratory Fort Rucker, Alabama 36362		12. REPORT DATE May 1983 13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This is a reprint from Volume 73, No. 3, Journal of the Acoustical Society of America, March 1983.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Noise
Hearing Loss
Acoustics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See reverse.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT:

Groups of human subjects were exposed for 8 or 24 hours to an octave-band noise centered at 63, 125, or 250 Hz. For a 24-hour exposure at 84 dBA, Temporary Threshold Shifts (TTS) increased for 8-12 hours and then either decreased or remained constant. Although TTS was less than 20 dB, complete recovery for many of the subjects required as long as 48 hours. Accordingly, the higher level exposure which was planned at 94 dBA for 24 hours was reduced to 90 dBA for 8 hours. For this condition, TTS increased throughout the 8-hour exposure. TTS from the 90 dBA noise for 8 hours exceeded the TTS produced by the 84 dBA; however, recovery from the 24-hour exposure required as long as 48 hours, whereas recovery from the 8-hour exposure required only 12-24 hours. Thus, the time required for recovery is determined in part by the duration of exposure. TTS was not always maximal ½-1 octave above the band of noise, but was maximal in the frequency regions of better auditory sensitivity (350 to 750 Hz). For the 250 Hz condition, TTS increased about 1.5 dB per dB increase in noise level, whereas for the 63- and 125-Hz conditions TTS increased less than 1 dB per dB increase in noise level. More data are needed to specify the relation between TTS and the level of low-frequency noises.

Temporary threshold shifts produced by exposure to low-frequency noises

John. H. Mills and J. David Osguthorpe
Department of Otolaryngology, Medical University of South Carolina, Charleston, South Carolina 29425

C. K. Burdick
U. S. Army Medical Research and Development Command, Fort Detrik, Frederick, Maryland 21701

J. H. Patterson and B. Mozo
U. S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama 36360

(Received 7 December 1981; accepted for publication 18 November 1982)

Groups of human subjects were exposed for 8 or 24 h to an octave-band noise centered at 63, 125, or 250 Hz. For a 24-h exposure at 84 dBA, temporary threshold shifts (TTS) increased for 8–12 h and then either decreased or remained constant. Although TTS was less than 20 dB, complete recovery for many of the subjects required as long as 48 h. Accordingly, the higher level exposure which was planned at 94 dBA for 24 h was reduced to 90 dBA for 8 h. For this condition TTS increased throughout the 8-h exposure. TTS from the 90-dBA noise for 8 h exceeded the TTS produced by the 84 dBA; however, recovery from the 24-h exposure required as long as 48 h, whereas recovery from the 8-h exposure required only 12–24 h. Thus the time required for recovery is determined in part by the duration of exposure. TTS was not always maximal $\frac{1}{2}$–1 oct above the band of noise, but was maximal in the frequency regions of better auditory sensitivity (350 to 750 Hz). For the 250-Hz condition, TTS increased about 1.5 dB per dB increase in noise level, whereas for the 63- and 125-Hz conditions TTS increased less than 1 dB per dB increase in noise level. More data are needed to specify the relation between TTS and the level of low-frequency noises.

PACS numbers: 43.66.Ed, 43.50.Qp [JH]

INTRODUCTION

While there are very many studies of noise-induced temporary threshold shifts most of these investigations have been concerned with effects produced by sounds in the frequency range of 0.5 to 4.0 kHz or less than 30 Hz (Jerger *et al.*, 1966; Johnson, 1982). Previous TTS studies which have used bands of noise or pure tones between 63 Hz and 250 Hz (Smith *et al.*, 1970; Ward, 1976; Burdick *et al.*, 1977; Patterson *et al.*, 1977) suggest that the rules for TTS's produced by mid- and high-frequency sounds apply to TTS's produced by low-frequency sounds with perhaps two exceptions. One is that whereas TTS is greatest 1/2–1 octave above the center frequency or upper cutoff frequency of the noise (Ward, 1962; Yamamoto *et al.*, 1970) TTS from low-frequency sounds is greatest in frequency regions of best auditory sensitivity (0.5–4.0 kHz) which can be 3–5 octaves above the exposure frequency. In other words the 1/2–1 octave shift rule may not apply to TTS's produced by low-frequency sounds. A second exception, although not of major concern here, is that a time-intensity trading rule(s) for exposure to noncontinuous low-frequency sounds must be significantly different from the rule(s) for noncontinuous exposures to mid- and high-frequency sounds (Ward, 1976).

While there are few TTS data on the effects of low-frequency sounds, there are provocative data on permanent effects (Burns and Robinson, 1970). In this large scale industrial study, audiograms from workers exposed to noises with energy concentrated in the low frequencies (downward sloping spectra) were compared with audiograms from workers exposed to noises with energy concentrated in the high frequencies (upward sloping spectra). Audiograms from these groups were identical. That is, noise-induced permanent threshold shift (NIPTS) was about 10 dB at 4.0 kHz and decreased as the test frequency was increased or decreased. It was concluded that NIPTS will always be greatest at 4.0 kHz regardless of the spectrum of the noise, and that A-weighted sound levels provide an accurate assessment of noise levels with respect to the production of permanent threshold shifts. Some comments about these results may be helpful. As Burns and Robinson state, the downward sloping noises had significant amounts of energy at frequencies above 1.0 kHz. Thus, it remains unclear as to whether the hearing loss at 4.0 kHz was due to the energy concentrations in the low frequencies or to the presence of high-frequency noise. Moreover, there remains the issue of the ability of measures of auditory sensitivity at low frequencies to detect injuries of the mid-to-apical region of the cochlea. Bredberg (1968) shows, for example, persons with hearing levels of 0–5 dB at 125–500 Hz but with as many as 50% of the outer hair cells missing in apical regions of the cochlea. Given the observations of Bredberg on human subjects, one should probably at least consider the possibility that the hazardous effects of the "downward sloping noises" of Burns and Robinson were underestimated.

Another reason for our interest in TTS produced by exposure to low-frequency noise comes from some of the unusual responses of the auditory system to low-frequency sounds. Loudness and masking data for signals less than about 250 Hz are notably different from loudness and masking data for signals between 500 and 4000 Hz. For example, the relation between loudness and signal intensity for a 100-

Hz tone is significantly different from the relation at 1.0 kHz (Hellman and Zwislocki, 1968), and debate persists about the shape of the equal-loudness contour at 100 Hz and below (Green, 1976). In masking, the critical ratio or the signal-to-noise ratio at masked threshold (Hawkins and Stevens, 1950) decreases systematically from 8.0 to about 0.2 kHz and then increases (see Sharf, 1970). The reasons for the unusual behavior of masking and loudness at low-frequencies include the shape of the audibility curve (Zwislocki, 1979), and standing wave patterns in the cochlea produced by wave reflections from the heliocotrema. A confounding factor is technical, especially measurement difficulties at such long wavelengths. Given the uncertainty in loudness and masking data at low frequencies, it seems reasonable that TTS's produced by exposure to low-frequency noises may have unusual characteristics in addition to the absence of the $\frac{1}{2}$–1 octave shift.

I. METHODS AND PROCEDURES

The methods and procedures used here are straightforward and similar in many respects to those given previously (Mills *et al.*, 1979; Mills *et al.*, 1981). In addition to the auditory measurements described below some nonauditory measurements were made also (heart rate, blood pressures, catecholamines, and cortisol). These are described elsewhere (Osguthorpe and Mills, 1982).

A. Subjects

Subjects were 52 male students between the ages of 18–22 who were recruited within the community. They were compensated at a rate of $3.50/hour. Individual subjects were required to have hearing threshold levels within $\pm$ 10 dB of audiometric zero (ANSI-S3.6., 1969) at frequencies from 125 to 4.0 kHz. To obtain 52 subjects, over 100 were screened. Most rejections were due to hearing threshold levels in excess of 10 dB usually at frequencies above 3 kHz. A few subjects were rejected for failure to keep appointments and poor reliability in audiometric measurement. Four subjects were withdrawn during the noise exposure. Two were withdrawn because of parental concern and two because of bizarre audiograms possibly related to a noise-induced tinnitus.

B. Exposure to noise

Subjects were exposed in groups of two in one room on the second floor of a two-story structure. The noise exposure room was equipped with 2 cots, 1 desk, a refrigerator, and toilet facilities. Subjects read, slept, played cards, etc. In this room loudspeakers had been placed strategically so as to achieve a constant sound field in the space occupied by the subjects. Noise generating equipment and test facilities were located on the ground floor. A-weighted levels and octave-band levels were measured at several locations. Range of levels in the space occupied by the subjects did not exceed 2 dB. White noise was filtered to obtain octave bands with measured center frequencies of 63, 125, and 250 Hz ($\pm$ 5 Hz), and a rejection rate of 24 dB/octave. Subjects were exposed for 24 h at 84 dBA or 8 h at 90 dBA to each of the octave bands (cf. = 63, 125, 250 Hz). There were 7–8 subjects/condition. Originally it was planned to expose subjects at 80 dBA and 90 dBA for 24 h; however, a pilot study ($N = 3$) for a 63-Hz exposure at 80 dBA for 24 hrs revealed no measurable TTS's. Accordingly, the level was raised to 84 dBA in the experiments reported here. Also, in the present experiment recovery of TTS from the 84-dBA exposure for 24 h required greater than 16–24 h. To insure recovery within 16–24 h, the exposure planned for 90 dBA for 24 h was reduced to 8 h. The 63-Hz exposure at 90 dBA interfered with threshold measurements, and it was necessary to attenuate the noise during threshold determinations which are described below. One additional group of subjects ($N = 6$) was exposed without interruption to the 63-Hz noise at 90 dBA for 8 h.

C. Auditory measurements

Pre-exposure measurements of auditory sensitivity were made daily over at least a 2-day period which preceded the noise exposure. Earphone placement was also varied so as to achieve at least five pre-exposure measurements of auditory sensitivity. The mean of these measures was used as the pre-exposure measurement of auditory sensitivity. A final pre-exposure audiogram was taken immediately before the exposure and used as a check on reliability. Discrepancies greater than $\pm$ 3 dB resulted in rejection of the subject and/or additional testing. Auditory sensitivity was measured by means of sweep-frequency (Bekesy) audiometry (Demlar, model 120). Below 250 Hz, auditory sensitivity was measured at 90, 125, and 180 Hz by means of fixed frequency Bekesy audiometry (Grason-Stadler, model E800). The tone was gated with an on time of 250 ms and a duty cycle of 50%. For the last 24 hours prior to the noise exposure, subjects were required to wear an earplug (EAR) in the test ear (ear with the better auditory sensitivity) so as to insure that the test ear was rested. The earplug provided at least 20–40-dB attenuation at frequencies above 500 Hz and less than 10 dB at 63 Hz.

During the noise exposure auditory thresholds were measured during periods of quiet interspersed within an exposure. At a prescribed time, a subject was removed from the noise for about 10 min during which thresholds were measured. Thus threshold shifts reported in this paper were recorded at post-exposure times between about 2 and 10 min and hereafter are called 4 min (TTS_4). The time spent away from the noise was always recorded and the total duration of the exposure was corrected (a 7-min increase in duration for every 3 min of recovery).

II. RESULTS

Figure 1 (panel B) shows TTS at the test frequency of maximum shift for the 90-dBA condition as a function of the duration of the exposure. The center frequency of the noise is the parameter. With the exception of one irregularity (63-Hz condition at 4–7 h) TTS increases throughout the exposure. The 3- to 4-dB differences observed between conditions here and elsewhere in the paper are not considered meaningful

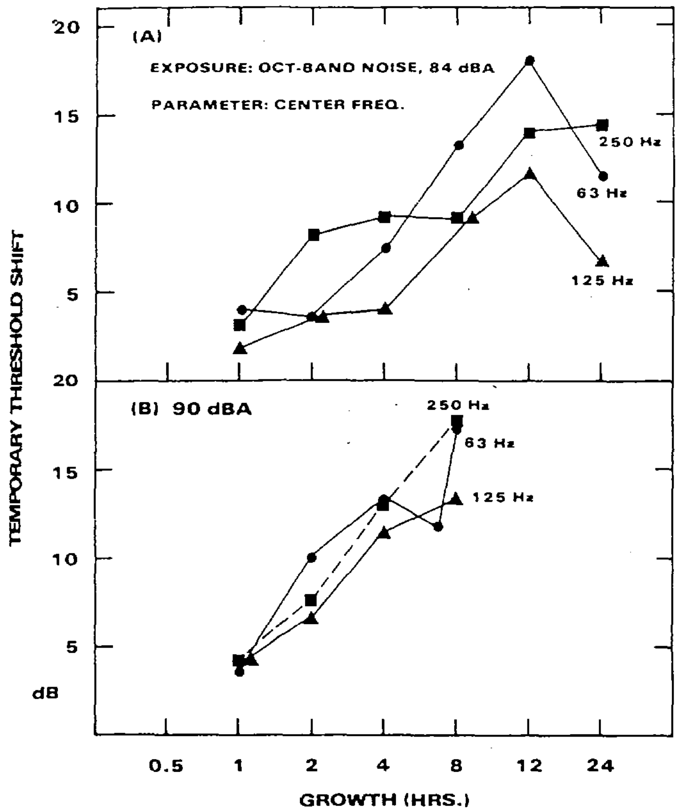

FIG. 1. TTS at the test frequency of maximal shift as a function of the duration of exposure. The A-weighted sound pressure level of the noise is 84 dB in panel A (top half) and 90 dB in panel B (bottom half). The parameter is the center frequency of the octave-band noise. The noise had a rejection rate of 24 dB/oct. $N = 8$ males datum point except at 63 Hz, 8 h where $N = 6$. Medians are reported at 8 h,std. deviations are 5.8 to 6.2 dB.

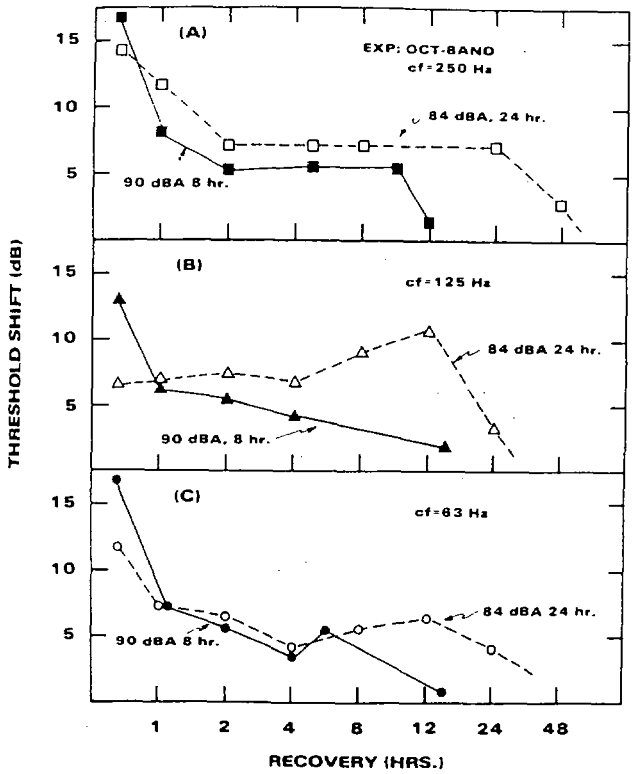

FIG. 2. Recovery of TTS at the test frequency of maximal shft after exposure to an octave-band noise for 8 or 24 h. Panel A, 250 Hz; panel B, 125 Hz; panel C, 63 Hz. Medians are reported.

inasmuch as the range of TTS values is 12 dB, the semi-interquartile range varies between 3 and 6 dB, and standard error of the mean varies from 2.00–2.75 dB. Variability of this magnitude is common in TTS experiments. Accordingly, differences between conditions of less than 5 dB (about two standard errors) are not viewed as meaningful. A rigorous statistical treatment of the data has not been attempted inasmuch as the sample size is only 6–8 subjects/condition.

Figure 1 (panel A) shows TTS for the 84-dBA condition. These results are not straightforward. For the 250-Hz condition, TTS is 8 dB after the first 2 to 8 h of the 24-h exposure, and then increases to 14 dB between 12 and 24 h. At the 125-Hz condition, TTS is only barely measurable after 4 h of exposure, increases from 4 to 12 h, and then decreases. TTS for the 63-Hz condition increases between 2 and 12 h, and then decreases. It may be worthwhile to rank-order the three bands of noise with respect to TTS. For an exposure of 4 h, the 250-Hz band produces the most TTS, then the 63-Hz band, and finally the 125-Hz band. At a duration of 12 h, the 63-Hz band produces the most TTS followed by the 250-Hz band, and finally the 125-Hz band. In different words, for the 84-dBA exposure the rank-ordering changes as the duration changes. It is not clear whether the differences between the conditions of Fig. 1 (B) are indicative of sampling variability or "real" frequency effects.

Figure 2 (panels A, B, C) shows recovery from TTS. These recovery curves show at least one consistent result, namely that recovery after the 24-h exposure at 84 dBA requires more time than recovery after the 8-h exposure at 90 dBA. This result is most obvious for the 250- and 125-Hz exposures where the 24-h exposure at 84 dBA produces significantly less TTS than the 8-h exposure at 90 dBA. Data of Fig. 2 show also that for all conditions recovery to within 2 dB of pre-exposure values occurred within 48 h for the 24-h exposure at 84 dBA and within 12 h for the 8-h exposure at 90 dBA. Another possibly remarkable feature of the recovery data is shown on panel B of Fig. 2. Note that for the 125-Hz condition TTS actually increased by 4 dB between post-exposure times of 4 and 12 h. It is not clear whether this increase represents measurement error or is an indication of a further deterioration of the ear after termination of the exposure.

Whereas a rank-ordering of the exposures in terms of the growth of TTS produced unreliable results especially for the 84-dBA exposures, a rank-ordering in terms of recovery produces a straightforward result. At post-exposure times of 2–12 h TTS was equivalent. Similarly, for the 84-dBA exposure the differences in TTS between exposure conditions are within $\pm$ 2 dB between 1–12 h of recovery.

Figure 3 shows the "TTS audiogram" produced by the 84-(panel A) and 90-(panel B) dBA exposures. The parameter is the center frequency of the octave-band noise. The data in panel A for the 84-dBA exposure are averaged across measurements made after 8, 12, and 24 h of exposure whereas the data in panel B are for an 8-h exposure. For both the 84- and 90-dBA exposures TTS is largest between about 350

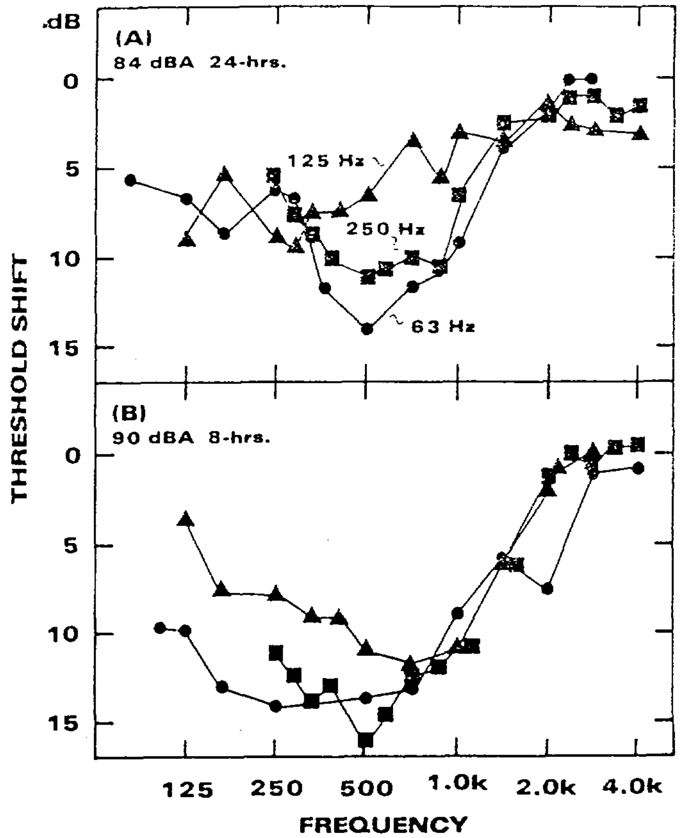

FIG. 3. TTS at different test frequencies. Panel A shows results for the 84 dBA exposure. Results have been averaged across 8, 12, and 24 h of exposure. Panel B shows results for 90 dBA exposure for 8 h. Parameter in both panel A and panel B is the center frequency of the octave-band exposure.

and 750 Hz, and not necessarily at the test frequency $\frac{1}{2}$ to 1 octave above the center frequency of the noise. One possible exception is the 125-Hz exposure at 84 dBA where TTS is 9 dB at 125 and 250 Hz, and 7.5 dB between 250 and 500 Hz. Another possible exception is at 500 Hz for the 250-Hz exposure. TTS is not measurable (5 dB) at test frequencies above 2.0 kHz except for the 63-Hz exposure at 90 dBA. In this case, TTS is equal or nearly so between 180 and 750 Hz and then decreases with an irregularity or discontinuity at a test frequency of 2.0 kHz. This irregularity, although small in magnitude, occurred for five of the six subjects. For the 90-dBA exposures (panel B) differences between conditions are most obvious at test frequencies below about 250 Hz. These differences reflect the spectrum of the noise. At test frequencies of 750 Hz and 1.0 kHz, however, the values of TTS are nearly identical. In other words, the TTS between about 750 and 1000 Hz is independent of the spectrum of the noise.

A crude estimate of the relation between TTS at the test frequency of maximum shift and noise level can be obtained by a comparison of TTS after 8-h exposure at 84 and 90 dBA. As shown on Table I, TTS increased when the noise level was increased from 84 to 90 dBA. The magnitude of the increase appears to be related to the center frequency of the noise. The slope increases from 0.67 at 63 Hz, to 0.83 at 125 Hz, and to 1.5 at 250 Hz. A more detailed treatment of the relation between noise level and TTS is hampered by the absence of data for a 24-h exposure at 90 dBA, by our inability to produce more intense low-frequency noises and therefore larger TTS's, and by the absence of data for TTS's less than 10 dB.

TABLE I. TTS and noise level.

	Octave-band frequency		
	63	125	250 Hz
TTS, 8 h, 84 dBA	13	9	9
TTS, 8 h, 90 dBA	17	14	18
Estimated slope	0.67	0.83	1.5

III. DISCUSSION

Previous TTS data from human subjects exposed to noise for 4–24 h (see Mills *et al.*, 1979; Patterson *et al.*, 1977) would suggest that TTS would increase for about 8–12 h and then reach a plateau or asymptote. Discontinuities in the growth curves would also be expected, particularly a 3 dB or so "overshoot" of the plateau or asymptote. Thus the data reported on Fig. 1 are consistent with the results of previous experiments. Some of the results of the 84-dBA exposures are difficult to discuss, particularly the shapes of the growth curves during the first 4 h of exposure and when one compares the data points at 4 h for 125 and 250 Hz. Moreover, it is difficult to assign the differences in the shapes of the growth curves for the 84-dBA exposures to procedural artifacts. Perhaps a sampling error is operating and a much larger N is needed.

The recovery data were consistent in many respects with previous data in that the time required for recovery was related to the duration of exposure (Mills *et al.*, 1970; Ward, 1970; Melnick, 1976, 1977; Nixon *et al.*, 1977). That is, recovery from the 84-dBA exposure for 24 h required 24–48 h whereas the recovery from the 90-dBA exposure for 8 h was complete by 12–24 h. It remains unclear whether recovery from long-duration exposures to low-frequency noise requires more time than recovery from high-frequency exposures. When the present data are compared to data from high exposures obtained using nearly identical experimental procedures (Mills *et al.*, 1979), then one can support the hypothesis that recovery from low-frequency exposures requires more time. When the present data are compared to data from high-frequency exposures obtained under different experimental procedures (Melnick, 1976, 1977) then the hypothesis is not supported.

An issue in human TTS experiments centers around the risks presented to the subjects. Can human subjects be used without creating a significant risk of permanent hearing loss and permanent injury to the inner ear? The present results suggest that the risk to the subjects is minimal. For example, all subjects recovered to within 2 dB of pre-exposure thresholds within 12–48 h after termination of the exposure. In other words, 0-PTS was produced. Moreover, not only was there an absence of PTS but the rates of recovery of TTS were faster than the rates observed in animals who had 0-PTS and small losses of outer hair cells (see Eldredge *et al.*, 1973). If the subjects of the present experiments had taken 3–

7 days to recover completely (PTS = 0 dB) rather than 2 days, the possibility of permanent injury to the inner ear still could not be eliminated.

In most experiments where the exposure has a spectrally dominant peak, TTS is maximal ½ to 1 octave band above that peak or above the upper cutoff frequency of the noise band (Davis *et al.*, 1950; Ward, 1962; Yamamoto *et al.*, 1970). Sometimes a second maximum is observed at frequencies nearly 3 octaves above the peak (see Mills *et al.*, 1979). In the present data the most striking features of the TTS audiograms were that the greatest TTS was observed between about 300 and 750 Hz regardless of the center frequency of the exposure, and with one exception TTS was not measured at test frequencies above about 2 kHz. The absence of the dominant peak in the TTS audiogram may be due to a number of factors. One of the more likely possibilities for maximal TTS in the 300–750 Hz region is the difference in auditory sensitivity between, for example, 90 and 750 Hz. This difference may be as large as 50–55 dB and is indicative of the acoustic properties of the external and middle ear (Zwislocki, 1979). Thus, while the noise had spectral peaks at 63, 125, and 250 Hz when measured in the sound field, the spectral peaks when measured at the input to the cochlea would be much less prominent. The absence of TTS at frequencies above 2.0 kHz for the 125 and 250 Hz exposures is inconsistent with expectations based on previous data (Burdick *et al.*, 1978; Patterson *et al.*, 1977; Mills *et al.*, 1979); however, the notch (for 5 of 6 subjects) in the TTS audiogram at 2.0 kHz for the 63-Hz exposure corresponds exactly to earlier predictions (Mills *et al.*, 1979) as well as to much earlier data (Smith *et al.*, 1970) showing a 5-dB notch in the TTS audiogram at 2.0 kHz produced by exposure to a 70-Hz tone. There are no obvious explanations for this equivocal support of earlier data and our expectations.

Thus uncertainties remain not only about the spread of TTS along the frequency dimension but also about permanent effects in the frequency dimension (see Liberman, 1982). The uncertainties involve empirical observations and a theoretical basis for the presence or absence of these observations, especially the 1/2–1 octave shift. Also, the inconsistent observation of a second maximum in the TTS audiogram is an enigma particularly because recent anatomical studies consistently show injured or missing sensory cells in the base and apex of the cochlea but not in mid-cochlear regions. In addition to sensory cells, Salvi *et al.* (1982) reports damaged cilia of sensory cells only in the apex and in the base after exposures to a low-frequency noise.

On the one hand, the impression is that 90-dBA exposures at 63, 125, or 250 Hz are equivalent or nearly so when comparisons of TTS are made at the test frequency of maximum shift. Similarly, an 84-dBA exposure at 250 Hz and an 83-dBA exposure at 4.0 kHz (Mills *et al.*, 1979) are nearly equivalent in terms of TTS at the test frequency of maximum change. On the other hand, if exposures are judged not on the basis of the TTS at the frequency of the maximal shift but on the "TTS audiogram" then an entirely different ranking (most to least TTS) occurs as follows: 63, 125, and 250 Hz, and 2.0 kHz and 4.0 kHz. Stated differently, a much greater region of the cochlea is affected by 63 Hz than by 4.0 kHz, and therefore, the number of sensory cells and other elements at "potential risk" is significantly greater with low-frequency exposures. Thus a low-frequency noise may present greater risk when risk is defined not by overall noise levels but in terms of the spread of TTS and perhaps the time required for recovery as well.

A. TTS and level of the noise

Previous results for humans (0.5–4 kHz) and animals (0.063–4 kHz) (Burdick *et al.*, 1977; Patterson *et al.*, 1977; Mills *et al.*, 1979, 1981) indicate that after 8–24 h of exposure, TTS increases at 1.5–2.0 dB for every 1 dB increase in noise level above a "safe" or "critical" level. Linear and curvilinear extrapolations are used to specify safe or critical levels. These are defined as those levels of noise which produce a TTS of 5 dB or less when the exposure duration is 8 h or longer. Only the data for the 250 Hz conditions were consistent with previous results and our expectations. Application of the linear and curvilinear procedures (see Mills *et al.*, 1981) to the 250-Hz data gives an estimated critical level of 78–80 dBA. In other words, to produce a median TTS (5 dB), an octave-band noise centered at 250 Hz should have a level of 78–80 dBA.

For noises centered at 63 and 125 Hz the relation between noise level and TTS is unclear. In TTS experiments where the median TTS's exceed 10 dB, an observed slope of less than one is a novel event and is difficult to explain. While the possibility of sampling error can not be eliminated, we are now inclined to believe that the relation between noise level and TTS's of 0–30 dB produced by low-frequency noise (125 Hz) may be different than that for TTS's produced by noises in the 250–4000 Hz range. This unusual behavior of TTS may or may not be related to the unusual behavior of other auditory phenomena at low frequencies, for example, the growth of loudness (Hellman and Zwislocki, 1968; Green, 1976) and critical ratios in masking (Sharf, 1970).

B. Miscellaneous comments

An unsolicited response from many of the subjects involved the sensation of a "tremendous pressure build-up" in the ear, particularly for the 63-Hz exposure. These informal reports confirmed the impressions of the experimenters. Interestingly, while the nonacoustic sensation was similar to the "pressure build-up" in the middle ear associated with altitude changes, the sensation could not be eliminated by opening of the eustachian tube by swallowing, yawning, or by the Valsalva technique. A more vigorous evaluation of the "sensation" is planned in future experiments.

An additional point of some interest involves a number of basic questions concerning the relation between anatomical integrity of the cochlea and the detection of auditory signals. For example, we can not state that the "unaffected" basal region of the cochlea was not used to detect tones less than 500 Hz. A masking paradigm is needed to eliminate the possibility of "basal region detection." Also, PTS's can be as small as 10 dB at 250 or 125 Hz and as many as 50%–65% of the outer hair can be missing (Bredberg, 1968). Thus it is possible that our estimates of the effects of the low-frequency noises and the estimates of others (for example, Burns and Robinson, 1970) are underestimates, and that certain physiological or other criterion measures would be more sensitive to acoustic injury of the ear. This possibility is supported by some pilot results on the effects of a 63-Hz noise as indicated by single-unit and gross physiology of the auditory nerve and sensory cell counts (Schmiedt, personal communication). In regard to the latter, gerbils had injuries (outer hair cells) in the apical region and in the base. Single units ranged from normal in most respects to abnormal tips of tuning curves and bizarre patterns of two-tone suppression. These results suggest additional physiological study of the effects of a 63-Hz noise, and that a 63-Hz noise may produce effects unlike those associated with higher frequency noises. We are reluctant, therefore, to claim that the effects of a 63-Hz noise and other low-frequency noises are well known given the data currently available. Additional experiments with human subjects are needed using low-frequency noises, especially 63 and 125 Hz. The experimental issues are the relation between TTS (5–30 dB) and noise level, the spread of TTS with frequency, and the rate of recovery of TTS. These experiments can be done with human subjects but not easily. The experimenter is severely restricted in the range of noise levels and durations that are both technically possible and ethically justifiable. In addition, the acoustic effects a 63- Hz noise are diffuse (wavelength at 63 Hz is about 17 ft) and disruptive to many activities in the vicinity of the experiment, and therefore, many of those activities must be terminated when the exposure is in progress. With all of these constraints it is possible and worthwhile to obtain additional TTS data from carefully selected low-frequency exposures.

ACKNOWLEDGMENTS

M. Bergevin and Laura Privitera recruited the experimental subjects and assisted in the data collection. Larry Kulish assisted in data collection and analyses. Supported by Contract No. DAMD 17-79-C-9180, U.S. Army Medical Research and Development Command. Pilot studies were supported by a grant from the National Institute of Environmental Health Services to the Medical University of South Carolina.

American National Standard Institute (1969). "American National Standard specifications for audiometers," ANSI S3.6.

Bredberg, G. (1968). "Cellular pattern and nerve supply of the human organ of corti," Acta Oto-Laryngol. Suppl. 236, 135 pp.

Burdick, C. K., Patterson, J. H., Mozo, B. T., and Camp, R. T., Jr. (1978). "Threshold shifts in chinchillas exposed to octave bands of noise centered at 63 and 1000 Hz for three days," J. Acoust. Soc. Am. **64**, 458–466.

Burdick, C. K., Patterson, J. H., Mozo, B. T., Hargett, C. E., Jr., and Camp, R. T. (1977). "Threshold shifts in chinchillas exposed to low-frequency noise for nine days," J. Acoust. Soc. Am. Suppl. 1 **63**, S95.

Burns, W. and Robinson, D. W. (1970). *Hearing and Noise in Industry* (Her Majesty's Stationery Office, London).

Davis, H., Morgan, C. T., Hawking, J., Galambos, R., and Smith, F. (1950). "Temporary deafness following exposure to loud tones and noise," Acta Oto-Laryngol. Suppl. **88**, 57 pp.

Eldredge, D. H., Mills, J. H., and Bohne, B. A. (1973). "Anatomical, behavioral, and electrophysiological observations on chinchillas after long exposures to noise," Adv. Oto-Rhino-Laryngol. **20**, 64–81.

Green, D. M. (1976). *An Introduction to Hearing* (Erlbaum, Hillsdale, NJ), p. 284.

Hawkins, J. E., and Stevens, S. S. (1950). "The masking of pure tones and of speech by white noise," J. Acoust. Soc. Am. **22**, 6–13.

Hellman, R. P., and Zwislocki, J. J. (1968). "Loudness determination at low sound frequency," J. Acoust. Soc. Am. **43**, 60–64.

Jerger, J., Alford, B., Coats, A., and French, B. (1966). "Effects of very low frequency tones on auditory thresholds," J. Speech Hear. Res. **9**, 150–160.

Johnson, D. L. (1982). "Hearing hazards associated with infrasound," in *New Perspectives on Noise-Induced Hearing Loss*, edited by R. P. Hamernik *et al.* (Raven, New York), pp. 407–421.

Liberman, M. C. (1982). "Acute and chronic effects of acoustic trauma: Cochlear pathology and auditory nerve pathophysiology," in *New Perspectives on Noise-Induced Hearing Loss*, edited by R. Hamernik *et al.* (Raven, New York), pp. 105–135, 225–226.

Melnick, W. (1977). "Temporary threshold shift following 24-hr noise exposure," Ann. Otol. Rhinol. Laryngol. **86**, 821–826.

Melnick, W. (1976). "Human asymptotic threshold shift," in *Effects of Noise on Hearing*, edited by D. Henderson *et al.* (Raven, New York), pp. 277–290.

Mills, J. H., Adkins, W. Y., and Gilbert, R. M. (1981). "Temporary threshold shifts produced by wideband noise," J. Acoust. Soc. Am. **70**, 390–396.

Mills, J. H., Gilbert, R. M., and Adkins, W. Y. (1979). "Temporary threshold shifts in humans exposed to octave bands of noise for 16 to 24 hours," J. Acoust. Soc. Am. **64**, 1238–1248.

Mills, J. H., Gengel, R. W., Watson, C. S., and Miller, J. D. (1970). "Temporary changes in the auditory system due to exposure to noise for 16 to 24 hours," J. Acoust. Soc. Am. **48**, 524–530.

Nixon, C. W., Johnson, D., and Stephenson, M. (1977). "Asymptotic behavior of temporary threshold shift and recovery from 24-hr and 48-hr exposures," Aviat. Space Environ. Med., 311–315.

Osguthorpe, J. D., and Mills, J. H. (1982). "Non-auditory effects of low-frequency bands of noise," Otolarngol. Head Neck Surg. **90**, 367–370.

Patterson, J. H., Burdick, C. K., Mozo, B. T., and Camp, R. T., Jr. (1977). "Temporary threshold shift in man resulting from 4-hr exposures to octave bands of noise centered at 63 and 1000 Hz," J. Acoust. Soc. Am. Suppl. 1 **62**, S95.

Salvi, R., Perry, J., Hamernik, R. P., and Henderson, D. (1982). "Relationships between cochlear pathologies and auditory nerve and behavioral responses following acoustic trauma," in *New Perspectives on Noise-Induced Hearing Loss*, edited by R. Hamernik *et al.* (Raven, New York), pp. 165–188.

Schmiedt, R. A. (1982). (Personal communication).

Sharf, B. (1970). "Critical bands," in *Foundations of Modern Auditory Theory*, edited by Tobias (Academic, New York).

Smith, P. J., Harris, M. S., Russatti, J. S., and Myers, C. K. (1970). "Effects of exposure to intense low frequency tones on hearing and performance," Submarine Med. Res. Lab. Rep. No. 610.

Ward, W. D. (1976). "A comparison of the effects of continuous, intermittent, and impulse noise," in *Effects of Noise on Hearing*, edited by D. Henderson *et al.* (Raven, New York), pp. 407–420.

Ward, W. D. (1970). "Temporary threshold shift and damage-risk criteria for intermittent exposures," J. Acoust. Soc. Am. **48**, 561–574.

Ward, W. D. (1962). "Damage-risk criteria for line spectra," J. Acoust. Soc. Am. **34**, 1610–1619.

Yamamato, T., Takagi, K., Shoji, H., and Yoneda, H. (1970). "Critical bandwidth with respect to temporary threshold shifts," J. Acoust. Soc. Am. **48**, 978–987.

Zwislocki, J. J. (1979). "The role of the external and middle ear in sound transmission," in *The Nervous System Vol 3. Human Communication and Its Disorders*, edited by E. Eagles (Raven, New York), pp. 45–55.